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Amplitude Information From Doppler Color Flow Mapping Systems: A Preliminary Study of the Power Mode

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The flow of a saline-glycerin solution with sand particles through a continuous in vitro flow system was imaged by using two commercially available Doppler color flow mapping systems in a power mode (Toshiba SSH-160A and Advanced Technology Laboratories [ATL] Ultramark 9). The images generated from seven solutions with particle concentrations ranging from 0.0001×10^{12} to 6×10^{12} particles/liter and a mean velocity of 30 cm/s measured with use of pulsed Doppler ultrasound were used to examine the dependence of the power mode on particle concentration.

To examine the velocity dependence, 20 mean velocities ranging from 0.1 to 0.53 m/s (3 to 30 liters/min) and three particle concentrations (1, 3 and 6×10^{12} particles/liter) in the solution were used. The recorded images were digitized and analyzed off-line. The SUM values, or the adjusted color intensity levels in delineated areas of interest in the displayed flow, were compared. In general, the power mode was sensitive in displaying slower velocity flows; in the selected particle concentration and velocity ranges, it was both velocity and concentration dependent. The specific dependence differed for the two color flow mapping systems.

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The manufacturers of commercially available Doppler color flow mapping systems provide adjustable options, such as different instrument settings and color maps, to obtain visually pleasing images of blood flow. Information about velocity, direction, variance or variation in the velocities and amplitude or strength is obtained from an analysis of the differences in the transmitted and received sound waves from moving red blood cells in the flow. The Doppler color flow data are then superimposed over a two-dimensional echocardiographic image. A vast array of qualitative information is provided by these Doppler color flow images. However, the accessibility to quantitative information is questionable because of the dependence of the image on the options selected by the examiner. Furthermore, because of the extremely competitive nature of the Doppler color flow instrument market, the algorithms with which images are constructed from velocity information are largely proprietary. The user is faced with a "black box," producing images that, although visually appealing, may or may not be physiologically meaningful.

One option provided by several manufacturers that is not well documented is the power mode. This mode allows for the portrayal of amplitude information that is generated by the analysis technique but usually not displayed. It thus permits enhancement of low velocity flows with high amplitudes such as those found in patients with cardiomyopathy or atrial septal defect. This power mode theoretically displays only amplitude information and thus might be used to predict flow volumes, a use that might be helpful in the clinical setting, in estimating regurgitant volumes, for example. We began a study of this power mode to determine whether it presents pure amplitude information and thus is velocity independent and concentration dependent.

Methods

Flow system (Fig. 1). We imaged a saline-glycerin solution with sand particles (mean diameter 2 to 3 μm) moving through a Plexiglas tube (inner diameter 1 in. [2.54 cm]) in a continuous in vitro flow system with two commercially available Doppler color flow systems with a power mode (Toshiba SSH-160A and Advanced Technology Laboratories [ATL] Ultramark 9). Our aim was to examine the dependence of the power mode on particle concentration and velocity.

Instrument settings. Table 1 shows the available options on both the Toshiba and the ATL Doppler color flow mapping systems. The options used to display the color flow images were determined so that optimal color flow signals were displayed and the Doppler color flow images generated

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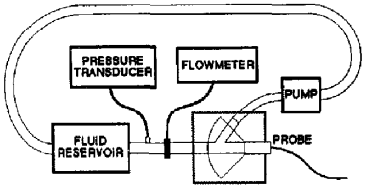


Figure 1. Schematic diagram of continuous in vitro flow system. The boxed inset on the schematic drawing (**lower right**) shows the examined flow area.

by the two systems were as comparable as possible. These settings remained fixed throughout the entire study.

Specifically, a 2.5-MHz transducer was used with the Toshiba SSH-160A color flow mapping system and the remaining instrument settings were adjusted so that a color depth of 19 cm, a color gain of 11, a color filter setting of 7, a pulse repetition frequency of 3 kHz, a Nyquist limit of 0.47 m/s, a color contrast of 3 and a color density setting of low-medium were used. A 2.25-MHz transducer was used with the ATL Ultramark 9 color flow mapping system. The depth was set at 19 cm and a color gain setting of 75 was used. The remaining settings were assigned as follows: a color wall filter of 300 Hz, a pulse repetition frequency of 3 kHz, a Nyquist limit of 0.52 m/s, a color map of 5, a color ensemble length of 12 and a frame rate of 8 Hz.

The transducer was securely mounted by fastening it with a clamp attached to a laboratory stand so that the flow observed in the color flow images was moving toward the transducer and the centerline of the viewing sector was oriented parallel to the direction of flow. The continuous flow system was turned on for approximately 10 min before scanning was performed so that the system achieved steady state conditions.

Particle concentrations. To examine the dependence of the power mode on particle concentration, a mean velocity of 30 cm/s measured with use of pulsed Doppler ultrasound was established in the in vitro flow system. Seven particle concentrations in the saline-glycerin solution moving through the in vitro system were used (0.0001, 0.01, 0.1, 0.5, 1, 3 and 6×10^{12} particles/liter) with a viscosity ranging from 3.5 to 4.5 cP. The system was emptied and flushed with each new solution before a different particle concentration was put into the system for examination.

Velocity ranges versus flow rate. To examine the velocity dependence, 20 mean velocities ranging from 0.1 to 0.53 m/s (3 to 30 liters/min) and three particle concentrations (1, 3 and 6×10^{12} particles/liter) in the saline-glycerin solution were used. This velocity range was selected so that the flows in which the slowest velocity detected with Doppler color flow imaging technique and the maximal velocity observed with this technique without the presence of aliasing were examined. After the flow was examined at the slowest velocity detected with Doppler color flow imaging, the flow rate was increased in increments of 0.5 liters/min until the electromagnetic flow probe measured 10 liters/min. The flow rate was then increased by increments of 1 liter/min up to 30 liters/min. The actual mean velocities in the flow were measured with the pulsed Doppler technique.

Flow image recordings. Images were recorded on videotape with a Panasonic AG-6300 and then digitized off-line on a Dextra D-200 cardiac analysis system. Because the flow was directed toward the transducer, only the red flow signals were displayed. An area of interest in the red flow signals was selected and the intensity levels (0 to 255) for the pixels contained in the area of interest were determined after each image was calibrated with respect to the color bar for the respective color flow mapping system. Each video record contains the flow image as well as the color bar associated with the image. The colors of the flow image were calibrated by utilizing the color bar associated with each image. The shades of red in the color bar were calibrated from 0 to 255 levels of intensity. Thus, the intensity levels of red in the area of interest are indicative of the intensity levels of the associated color bar with each image. Calibration of the color bar associated with each image was performed before SUM (see Appendix) was calculated. The calibration and determination of the intensity levels were performed with use of the software on the Dextra D-200.

Delineating the area of interest (Fig. 2). The area of interest was delineated by defining a rectangular area in the flow inside the tube at a constant distance from the transducer. The described area of interest was 60 pixels wide and 48 pixels deep and encompassed the entire tube width. Thus, it was made up of 2,880 pixels or consisted of an area equal

Table 1. Available Options on Toshiba SSH-160A and ATL Ultramark 9 Doppler Color Flow Mapping Systems

	Equipment Settings for Color Flow Mapping							
Equipment Used	Depth (cm)	Gain	PRF (kHz)	Frame Rate (Hz)	Filter settings	Nyquist Limit (m/s)	Contrast	Ensemble
Toshiba SSH-160A (range)	4–24	1–16	3–12	5–48	1–7	0.47–1.84	0–3	—
ATL Ultramark 9 (range)	1–22	0–100	0.6–10	3.3–31.0	100–600	0.07–1.20	—	7–32

ATL = Advanced Technology Laboratories; PRF = pulse repetition frequency.

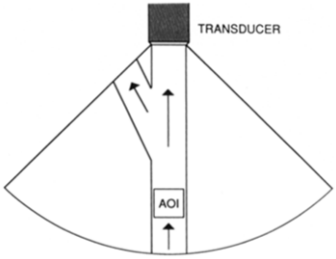


Figure 2. Delineation of an area of interest (AOI) in the displayed flow (arrows indicate flow direction).

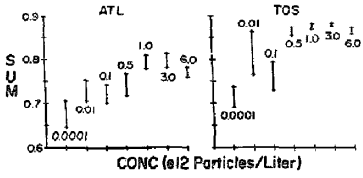


Figure 3. Dependence of the power mode on particle concentration. ATL = Advanced Technology Laboratories Ultramark 9 Doppler color system; CONC = concentration, e12 = $\times 10^{12}$; SUM = a dimensionless index created for comparison purposes only; TOS = Toshiba Medical Doppler color system.

to approximately 440 mm^2. Although our imaging chamber possessed a Y-branching conduit for outflow, the area of interest from which our data were taken was located far enough away from the conduit that laminar flow was observed without any deviation (or turbulence) of the flow pattern toward the conduit. The flow pattern had been confirmed by injections of dye into the flow system during previous experiments in this laboratory. The area of interest was located 12.5 cm from the transducer and 7.75 cm from the Y-branching conduit.

The calculations performed for each area of interest are listed in the Appendix. To examine the velocity dependence, the SUM results were compared with the mean velocity measurements. To evaluate particle concentration dependence, the SUM results were compared with particle concentrations and Bonferroni *t* tests were performed.

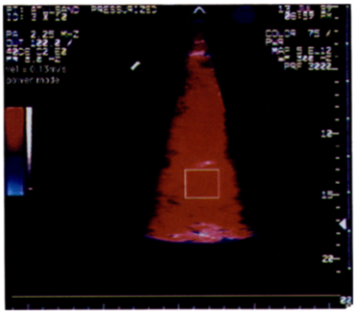
Results

Particle concentration dependence study (Fig. 3 and 4). No statistical differences ($p > 0.05$) were observed for the measurements made with the ATL Ultramark 9 color flow mapping system at the higher particle concentrations (6, 3 and 1×10^{12} particles/liter) (Fig. 3), but the statistical differences became significant ($p < 0.05$) for the measurements made at the lower concentrations (0.5, 0.1, 0.01 and 0.0001×10^{12} particles/liter) (Fig. 4). The intensity levels of the power mode display were significantly lower at a particle concentration of 0.0001×10^{12} particles/liter than were those produced at the other particle concentrations. However, the highest particle concentration, 6×10^{12} particles/liter, showed a decrease in the mean value of SUM (0.7748 ± 0.0039) as compared with the mean SUM values obtained at the particle concentrations of 3 and 1×10^{12} particles/liter (0.7911 ± 0.0044 and 0.7907 ± 0.0044, respectively). The results from this particle concentration, 6×10^{12} particles/liter, were not statistically different from results obtained with the solution containing 0.5×10^{12} particles/liter.

The study performed using the Toshiba SSH-160A color flow mapping system showed that the results for the four higher particle concentrations (6, 3, 1 and 0.5×10^{12} particles/liter) were not statistically different ($p > 0.05$) at the same flow rate. However, at the lower particle concentrations (0.1, 0.01 and 0.0001×10^{12} particles/liter), the results were statistically different ($p < 0.05$) from the results obtained with the higher concentrations. As observed with the ATL system, the SUM results (0.8665 ± 0.0037) for the higher concentration (6×10^{12} particles/liter) were slightly lower than the values obtained for the lower particle concentrations (3 and 1.0×10^{12} particles/liter) (0.8798 ± 0.0018 and 0.8772 ± 0.0033, respectively).

Significant differences ($p < 0.05$) in the mean SUM values with respect to concentration were observed only after the particle concentrations were reduced to $< 0.5 \times 10^{12}$ for ATL Ultramark 9 and $< 0.1 \times 10^{12}$ for the Toshiba system. Thus, changes in power information appear to be present only at the lower particle concentrations, suggesting that power mode depends on concentration only in this range.

Velocity dependence study (Fig. 5 and 6). The curves for the two Doppler color echocardiographic systems took the same general shape. Initially, the SUM values increased as the velocity increased until a specific velocity was reached and the SUM values then did not change despite changes in velocity. For all particle concentrations, the SUM value increased until a velocity of 0.36 m/s for ATL Ultramark 9 and 0.30 m/s for the Toshiba system was reached. A simple fit regression analysis was performed on the ascending portion of the curve (slope = 2.503 ± 0.165, $r = 0.94$ for ATL Ultramark 9 and slope = 6.514 ± 0.779, $r = 0.89$ for the Toshiba system) to show the strength of dependence on velocity and a descriptive analysis was performed on the portion of the data included in the plateau of the curve for each color flow mapping system. The ATL Ultramark 9 and the Toshiba color flow mapping systems had average SUM values of 0.7820 ± 0.0045 and 0.8665 ± 0.0041, respectively.



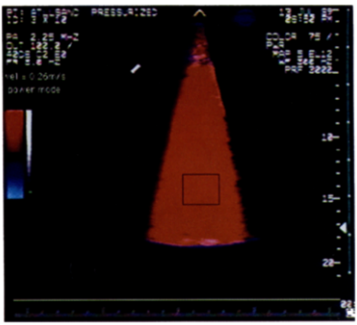
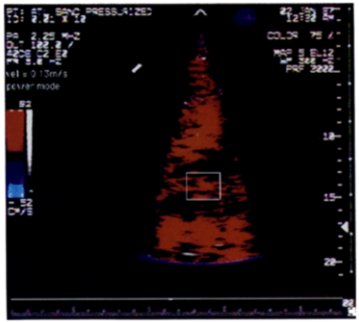


Figure 4. *In vitro study. Power mode display of flow* at a velocity (vel) of 0.13 m/s and particle concentrations of 3×10^{12} particles/liter (**upper panel**) and 0.01×10^{12} particles/liter (**lower panel**). The **rectangular square in both panels** represents the area of interest from which sample pixel velocity was taken.



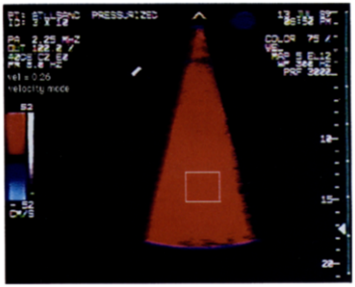


Figure 5. In vitro study. Power mode (**upper panel**) and velocity (vel) mode (**lower panel**) displays of flow at a velocity of 0.26 m/s and a particle concentration of 3×10^{12} particles/liter. **The rectangular square in both panels** represents the area of interest from which sample pixel velocity was taken. The location within the tube and the area of interest were the same in all cases.

for these data. Poor correlation coefficients resulted when a simple fit regression analysis was performed on the portion of the data contained in the plateau of the curve (slope = 0.0041 [$r = 0.39$] and 0.0051 [$r = 0.53$] for the ATL Ultramark 9 and the Toshiba system, respectively).

Discussion

Theoretically, amplitude information correlates with the number of particles that are moving in a flow field. With this information, the volume of the flow should be approximated by dividing the estimated number of particles in the flow by the particle density or the number of particles per volume of solution. Unfortunately, the majority of the commercial Doppler color flow systems do not display amplitude information even though the analysis techniques used, such as autocorrelation, generate it.

The power operating mode: its usefulness. Several commercial Doppler color flow systems have recently provided an option referred to as the power mode. This mode has not been well defined by the manufacturers, but it has been described by them and other investigators (1–4) as helpful in enhancing the display of low velocity flows with high amplitudes such as occur in patients with cardiomyopathy and atrial septal defect.

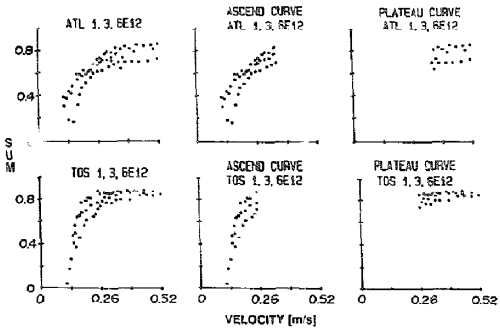


Figure 6. Dependence of the power operating mode on velocity. ASCEND CURVE = the ascending portion of the curve; PLATEAU CURVE = the flat portion of the curve; other abbreviations as in Figure 3.

Questions remain about the usefulness of this power mode. Does it display pure amplitude information and is it, therefore, velocity independent and concentration dependent? Because the power mode emphasizes the display of moving particles, it should depend strongly on particle concentration and if pure amplitude information is being displayed, the display should not be velocity dependent.

Doubts about the quantitative possibilities with the power mode also exist. For example, in an industrial review (5), one manufacturer suggested without supporting data that the power mode provides no additional qualitative and quantitative information than the velocity/variance operating mode. We, in fact, have found in previous experimental work in our laboratory (6,7) that qualitative results in terms of flow area measurements using the power mode on both the Toshiba SSH-160A and the ATL Ultramark 9 color flow mapping systems were not significantly different from those obtained using the velocity/variance mode despite the brighter flow areas displayed using the power mode.

Being able to quantitate the color image would have enormous potential in improving the diagnostic capabilities of Doppler color flow studies. Problems, however, exist with quantitating the color image because the image generated is strongly dependent on the instrument settings that the examiner manipulates to obtain a visually pleasing image and on the color flow mapping system itself. Therefore, as with the velocity/variance operating mode, the dependence of the power mode display on the color flow mapping system used and the instrument settings selected needs to be defined or bypassed before quantification is possible.

Relation between power mode and velocity and particle concentration. This preliminary study was conducted to define the relation or dependence of the power mode results on velocity and particle concentration for two specific color flow mapping systems. The results indicate that for both systems, the power mode is sensitive in displaying lower velocity flows; in the selected particle concentration and velocity ranges, it is velocity and concentration dependent. In addition, the specific dependence differs for the two color flow mapping systems. Figures 3 and 6 show the difference in the velocity and concentration dependence between the two systems. In general, the mean SUM values calculated for the ATL system were significantly lower than the values calculated for the Toshiba system. Therefore, the presentation of the amplitude information differed for the two systems. For this reason, a direct comparison could not be made and will not be possible until the exact algorithms used in the presentation of the amplitude data are known and the "raw" data can be compared.

The data displayed in Figures 3 and 6, however, did exhibit the same general trends despite the different systems used. For example, in Figure 3, the highest particle concentration, 6×10^{12} particles/liter, showed a drop in the mean value of SUM (0.7748 ± 0.0039 for the ATL system and 0.8665 ± 0.0037 for the Toshiba system) compared with the mean SUM values obtained at the particle concentrations of 3 and 1×10^{12} particles/liter (0.7911 ± 0.0044 and 0.7907 ± 0.0044, respectively, for the ATL system and 0.8798 ± 0.0018 and 0.8772 ± 0.0033, respectively, for the Toshiba system). The decrease in the SUM values may have occurred because of attenuation resulting from the large number of reflectors or possible oversaturation of particles at this concentration level and thus the reduction in the number of reflectors in solution.

Significant differences ($p < 0.05$) in the mean SUM values with respect to concentration were observed only after the particle concentrations were reduced to a specific concentration ($<0.5 \times 10^{12}$ for ATL Ultramark 9 and $<0.1 \times 10^{12}$ for the Toshiba system); assuming that the particles were uniformly

distributed in the solution, these results suggest that the power mode depended on concentration only at the lower ranges.

This study also showed that differences in the power mode display resulted only when large variations in the particle concentrations were present. For example, the results with the power mode differed significantly only when the particle concentration was decreased from 6×10^{12} to 0.5×10^{12} particles/liter for the ATL Ultramark 9 and from 6×10^{12} to 0.1×10^{12} particles/liter for the Toshiba system.

In Figure 6, the SUM values for both systems initially increased as the velocity increased until a specific velocity was reached and the SUM values did not change despite changes in velocity. For all particle concentrations, the SUM values increased until a velocity of 0.36 m/s for ATL Ultramark 9 and 0.3 m/s for the Toshiba system was reached. Therefore, our study showed that the power mode is strongly dependent on velocity at the lower velocity ranges and that after a specific velocity was reached, little variation was observed in the SUM values, and thus in flow area measurements, despite increases in velocity.

Previous studies. Our findings revealed that the velocity information plays an important role in the power mode display, confirming previous findings by Simpson et al. (2). They proposed that the power mode is velocity dependent and that the velocity dependence helps differentiate the real color flow display from the low amplitude noise signals, but they did not define the specific dependence of the power mode on velocity or examine the concentration dependence of the power mode results. However, they found that quantitative information (summation of pixel intensities) derived by using the power mode correlated better with the regurgitant stroke volume than did the driving pressure, which was opposite to the results that they found for the quantitative information (summation of pixel intensities) derived from the velocity/variance mode. From these findings, they suggested the possible use of the power mode in calculating regurgitant volume. Because we found that the displayed power mode results have limited dependence on concentration, we concluded that the possible use of this information to calculate regurgitant volume is questionable unless "true" amplitude information is obtained.

Limitations. Inaccuracies in the results of this study may have resulted from using digitized video-recorded images for analysis rather than using directly obtained digital information from the Doppler color flow system before the information was color-coded and converted to analog signals for display on the system monitor. Currently, available commercial color flow mapping systems with the power mode do not allow this type of information to be obtained.

In addition, the sand particles contained in the blood-mimicking fluid were assumed to be homogeneously mixed and to have the same reflectivity as that of red blood cells. Thus, the specific dependence of the power mode display on velocity and particle concentration in clinical situations may change, but the strength of the dependence of the power mode on these two variables should still prevail. Although cornstarch is commonly used in ultrasound studies, the particulate diameter is highly variable. Therefore, sand particles were utilized as reflectors in our blood-mimicking fluid to decrease the variability of particulate size.

Although pulsatile flow is physiologic, steady flow was intentionally chosen by us for this experimental study to isolate the effects of particle concentration and flow velocity. Another limitation was the difficulty in achieving identical baseline instrument settings and outputs for the two commercially available machines used in the present study. This occurred because of nonstandardization of instrument settings and processing variables, making it difficult to compare machines from different manufacturers. However, this does not represent a limitation in the design of the present study.

Conclusions. The results from the power mode available on the Toshiba and Advanced Technology Laboratories Ultramark 9 color flow mapping systems depend on velocity and have a limited dependence on concentration. In addition, this dependence on velocity and concentration differed for the two systems. These factors must be remembered when comparing the examinations performed on patients with this mode and on the different color flow mapping systems.

Our results in this preliminary study also show the importance of having manufacturers provide more information about the options available on their color flow mapping systems so that accurate and reliable data can be obtained and that studies performed on different machines can be easily and accurately compared.

We thank Luiz Pinherio, MD for drawing Figures 1 and 2 and U.S. Silica (Pacific, Missouri) for providing the sand particles for use in the blood-mimicking fluid.

Appendix

Calculations

The following calculation was performed for each area of interest.

$$\text{SUM} = \sum \frac{I_n}{I_{max} \text{ in color bar}} \times \frac{\text{No. of pixels for } I_n \text{ in area of interest}}{\text{Total no. of pixels in area of interest}},$$

where I_n (intensity level) increased from 0 to 255 and SUM was a dimensionless index, created for comparison purposes, whose limit approaches 1. An example of the calculation of the SUM value is given below.

Example:

Intensity Level (I_n) or Shades of RED	No. of Pixels
0	a
1	b
2	c
.	.
.	.
.	.
255	P_n

$$SUM = \frac{(0)(a)}{255\,2880} + \frac{(1)(b)}{255\,2880} + \frac{(2)(c)}{255\,2880} + \ldots + \frac{(255)(P_{255})}{255\,2880}$$

$$SUM = \frac{b + c2(c) + \ldots + (255)(P_{255})}{734400}$$

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